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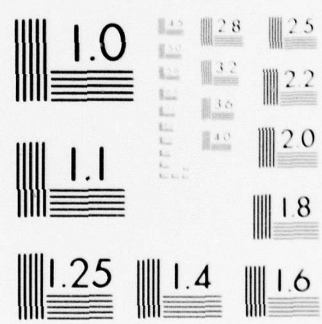

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CETA 79-2

A Method for Estimating Long-Term Erosion Rates From a Long-Term Rise in Water Level

by

J. Richard Weggel

COASTAL ENGINEERING TECHNICAL AID NO. 79-2

MAY 1979

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A method is presented for estimating long-term erosion rates resulting from a rise in sea level. The method is based on Bruun's (1962) method with an exponential curve fitted to the offshore beach profile. The exponential profile establishes the beach profile closure depth beyond which it is assumed waves do not move sand. An example problem using sea level rise data of Hicks (1973) illustrates application of the technique.

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PREFACE

This report presents a method for estimating long-term erosion rates resulting from a rise in sea level, based on Bruun's (1962) method with an exponential curve fitted to the offshore beach profile. The method is approximate and is intended to supplement conventional analyses of historical profile and shoreline changes rather than to supplant such analyses. The work was carried out under the coastal engineering research program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by J. Richard Weggel, Chief, Evaluation Branch, under the general supervision of N.E. Parker, Chief, Engineering Development Division.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: C = (5/9) (F -32).

To obtain Kelvin (K) readings, use formula: K = (5/9) (F -32) + 273.15.

SYMBOLS AND DEFINITIONS

A	long-term rate of sea level rise (feet per year)
B	distance from shore to the depth contour beyond which there is no significant sediment motion (feet)
d	water depth below which there is no significant sediment motion (feet)
e	base of the Napierian logarithms (2.71828. . . .)
h	height of beach berm or bluff (feet)
ℓn	logarithm to the base e
Δx	shoreline retreat rate (feet per year)
y	ordinate of the beach profile (feet)
y_o	datum correction factor used to fit beach profile to exponential curve (feet)
α	empirical coefficient that describes the rate at which water depth increases offshore (slope of beach profile plotted on semilogarithmic graph paper) ($feet^{-1}$)

A METHOD FOR ESTIMATING LONG-TERM EROSION RATES FROM A LONG-TERM RISE IN WATER LEVEL

by
J. Richard Weggel

I. INTRODUCTION

Bruun (1962) proposed a method for determining the distance a shoreline will retreat if the mean sea level rises slightly. His method is based on the assumption that the beach profile after the sea level rise will be identical to the original profile shifted upward and landward a specified amount. The landward shift of the profile represents the shoreline retreat. The total volume of beach material per unit length of beach involved in the profile shift can also be determined. This volume represents the volume of sand per unit length of beach that must be placed on a beach to extend the beach seaward to its location before the rise in water level. Application of Bruun's method requires that the water depth beyond which there is no significant sediment motion be determined and that the distance from shore to this depth contour be known. This paper proposes a reproducible procedure for establishing the shoreline retreat associated with a water level rise.

This procedure is applicable only to sandy beaches having an uninterrupted supply of sand. Any bluffs or dunes that are eroding should be of material essentially the same as the material on the active profile and the longshore transport should be in equilibrium; i.e., the longshore transport out of the beach segment should be balanced by the longshore transport into the segment. Also, since little is known about the rate at which profiles respond to changes in water level, the procedure should be used only for estimating long-term changes such as occur over a number of years rather than seasonal changes. The procedure is not a substitute for the analysis of historical shoreline and profile changes when the necessary data are available; it is intended to supplement such analyses or to provide an estimate of long-term erosion rates due to sea level rise when little or no historical data are available.

II. BRUUN'S METHOD

In estimating long-term erosion rates along Florida beaches, Bruun (1962) assumed that the erosion rates were the result of a long-term rise in the position of mean sea level with respect to the land. Such changes of sea level can result from either an increase in water level or by subsidence of the region adjacent to the sea. As the water level rises, the profile is assumed to move without changing its shape (a decline in water level will not reverse the process). It should also be emphasized that shorter term shoreline changes will occur independently of the sea level rise and shoreline retreat process; these changes may be much larger in magnitude than changes caused by sea level rise. The landward migration of a profile for an increase in water level is graphically shown in Figure 1. If the water level rises by an amount, A, the quantity of material

per unit length of shoreline needed to reestablish the bottom elevation over a distance, B, seaward from the shoreline is AB. The length, B, is the distance measured perpendicular to the shoreline out to the depth contour beyond which there is no significant sediment motion. The volume of sand per unit length of beach, AB, must be derived from the active profile by a recession of the profile. The amount of the recession, Δx, is determined by balancing the volume AB with the area between the two profiles. This area, given simply by $\Delta x(h + d)$, represents the volume of sand per unit length of beach needed to reestablish the beach to the original shoreline. Equating the two volumes gives

$$AB = \Delta x(h + d) , \tag{1}$$

or upon solving for Δx,

$$\Delta x = \frac{AB}{(h + d)} . \tag{2}$$

Application of equation 2 requires that the depth, d, and hence the distance, B, be known. Using the values of the trend of sea level at various U.S. coastal locations (App.) given by Hicks (1973), A can be determined. The following section provides a procedure for establishing d, and thus B.

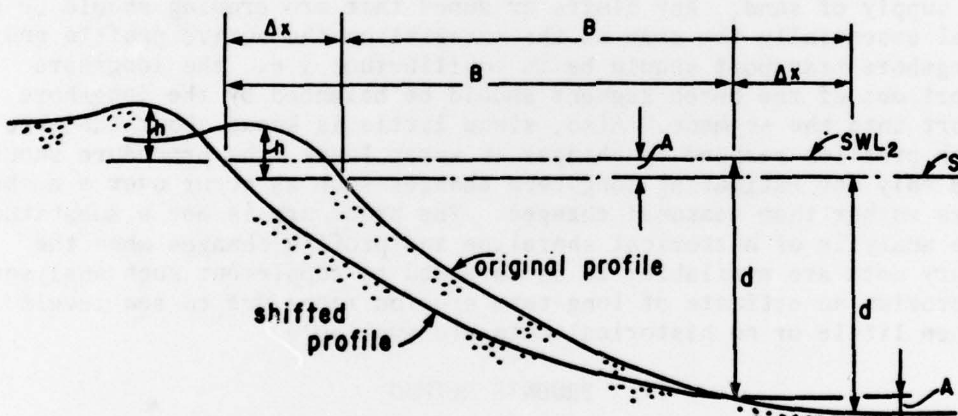

Figure 1. Similarity of profiles, Bruun's method.

III. SEAWARD LIMIT OF SEDIMENT TRANSPORT

Limited observations of offshore profiles indicate that they can frequently be described to a certain depth by a simple exponential decay equation. Small- to moderate-scale beach features such as bed forms and offshore bars tend to be perturbations on this general trend. Everts (1978) describes the geometric characteristics of profiles across the

Continental Shelf for numerous locations along the Atlantic and gulf shorelines, and finds that an exponential curve fits averaged profiles quite well across the nearshore segment of the profile. A preliminary view indicates that a semilogarithmic profile also fits data from the Pacific coast. In general, an equation of the form,

$$y - y_o = de^{-\alpha x} , \tag{3}$$

can be fitted to the profile data, where y is the vertical coordinate of the profile, x is the horizontal coordinate, y_o is a datum adjustment factor that must be established by trial and error, d is the depth at the seaward limit of effective sediment transport, and α is an empirical coefficient that describes the rate of increase in water depth with distance offshore. Other investigators have applied other equations to approximate the nearshore beach profile (e.g., Bruun, 1954; Resio, et al., 1974; Dean, 1977).

The method of fitting equation 3 to actual profile data is best illustrated by an example (Table). The table gives profile data at Ocean Beach, San Francisco, California, taken in November and December 1972. The data are averaged from three profile lines located about 1,500 feet (457 meters) apart. Columns 1 and 2 in the Table are the original average profile data. Column 3 represents a first approximation to determine the datum correction term, y_o. The first approximation is obtained by taking the datum at the elevation of the seawardmost point on the profile (i.e., assume y_o = -37.5 feet or 11.4 meters). Hence, column 3 is obtained by adding 37.5 to the values in column 2. The resulting profile is shown plotted (solid circles) on semilogarithmic graph paper in Figure 2. A line is fitted to the points of the profile in the nearshore region to obtain a correction to the first approximation. The correction, which is to be added to the first approximation values, is read from the fitted line at the seawardmost point of the profile (e.g., at 3,400 feet or 1,036 meters in Fig. 2). The 6.0-foot (1.83 meters) adjustment is added to column 3 of the table to obtain the second approximation given in column 4. A correction to the second approximation is subsequently obtained from a line fitted to the plotted second approximation values (see Fig. 2). The correction in the example is 1.5 feet (0.46 meter) which is added to the values in column 4 of the table to obtain a third approximation. Plotting the third approximation in Figure 2 indicates only a small change in the location of the fitted line. The value of y_o is thus found to be -37.5 - 8.1 = -45.6 feet (-13.9 meters); the depth beyond which significant sediment movement does not occur can be read from the y intercept of Figure 2 as d = 55.0 feet (16.8 meters). The value of α in equation 3 is obtained from the slope of the line in Figure 2. Hence, for the example,

$$\alpha = \frac{\Delta \ell n\ y}{\Delta x} = \frac{\ell n\ 55 - \ell n\ 10}{3025 - 0} = 0.000564 \tag{4}$$

where the y intercept and the point where the line crosses y = 10 have been used to evaluate the slope. The logarithm to the base e, ℓn, is

Table. Calculation of profile approximation (example problem).

(1) Distance offshore (ft)	(2) Depth below MLLW (ft)	(3) 1st approx. (ft)	(4) 2d approx. (ft)	(5) 3d approx. (ft)
		+37.5	+6.0	+1.5
0	+33.0	70.5	76.5	78.0
200	+ 4.0	41.5	47.5	49.0
400	- 2.0	35.5	41.5	43.0
600	- 6.0	31.5	37.5	39.0
800	- 9.0	28.5	34.5	37.0
1,000	-12.5	25.0	31.0	32.5
1,200	-14.0	23.5	29.5	31.0
1,400	-14.5	23.0	29.0	30.5
1,600	-17.5	20.0	26.0	27.5
1,800	-22.0	15.5	21.5	23.0
2,000	-25.5	12.0	18.0	19.5
2,200	-29.5	8.0	14.0	15.5
2,400	-31.5	6.0	12.0	13.5
2,600	-34.0	3.5	9.5	11.0
2,800	-35.0	2.5	8.5	10.0
3,000	-36.0	1.5	7.5	9.0
3,200	-36.5	1.0	7.0	8.5
3,400	-37.5	0.0	6.0	7.5

used since equation 3 is expressed in terms of e. Therefore, for the example, equation 3 may be written

$$y + 45.6 = 55.0e^{-0.000564x} \quad (5)$$

IV. COMPUTATION OF LONG-TERM EROSION RATES

To compute the long-term erosion rate from equation 2, the distance from shore to the 55-foot contour must be obtained from a hydrographic chart and the long-term trend in sea level must be known. For the San Francisco area, the long-term trend in sea level between 1898 and 1971 is a rise of 0.0064 foot (0.00195 meter) per year. The trend in the more recent period from 1940 to 1971 has been 0.0054 foot (0.00165 meter) per year. (See the App. which is reproduced from Hicks, 1973.) At Ocean Beach, the distance offshore to the 55-foot contour varies, but is approximately 32,600 feet (9,936 meters), thus B = 32,600. Solving equation 2,

$$\Delta x = \frac{0.0054\ (32{,}600)}{(23.0 + 55)} \simeq 2.3 \text{ feet (0.701 meter) per year},$$

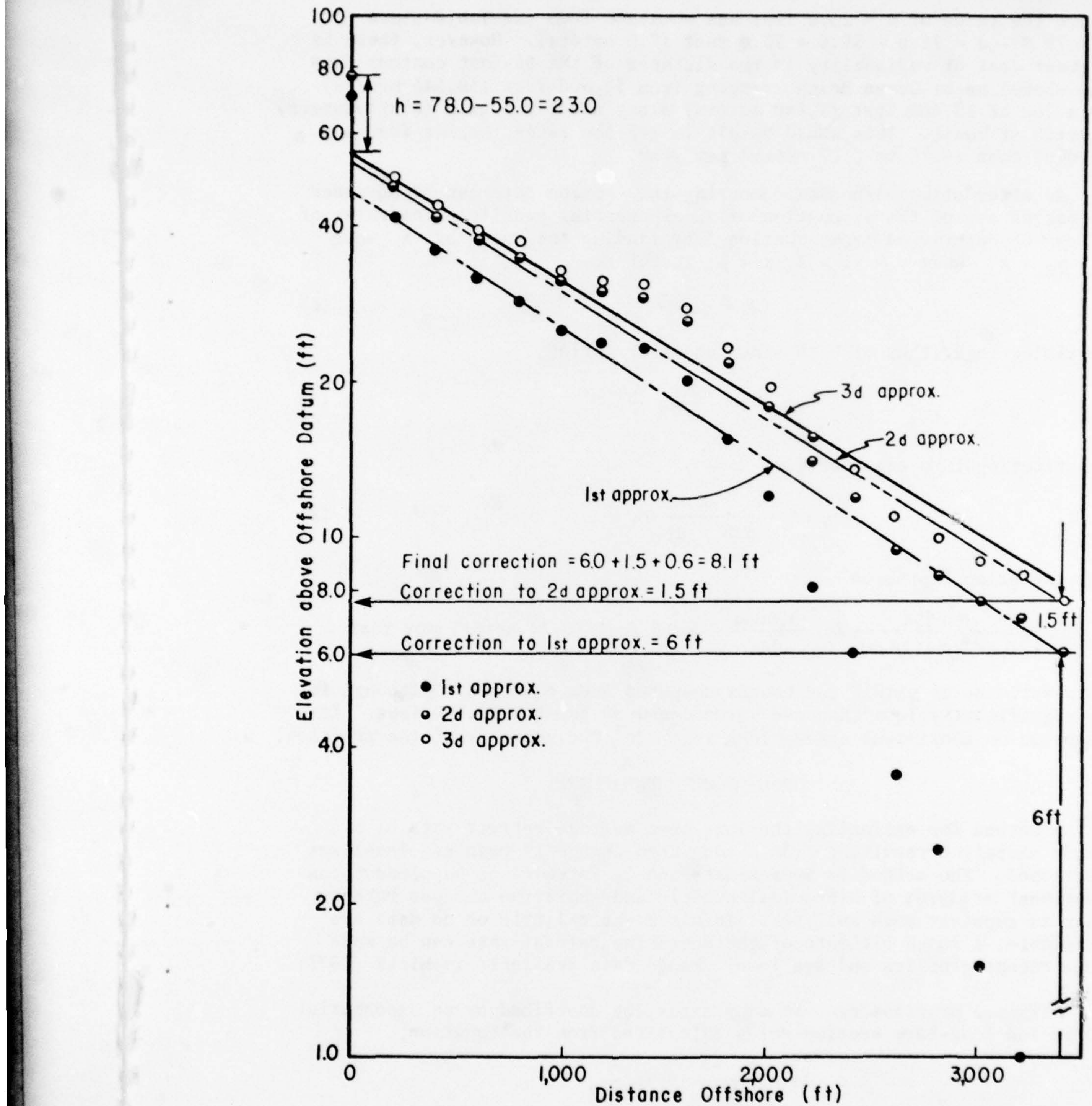

Figure 2. Successive approximations to fit exponential curve to profile data (Ocean Beach, San Francisco, California).

where the value of h = 23.0 feet was obtained from the Table since h = 78.0 - d = 78.0 - 55.0 = 23.0 feet (7.0 meters). However, there is a great deal of variability in the distance of the 55-foot contour from the shoreline at Ocean Beach, ranging from 34,600 feet (10,546 meters) to a low of 12,600 feet (3,840 meters) along about a 5-mile (8 kilometers) stretch of coast. This would result in erosion rates ranging from 2.3 to 0.87 foot (0.73 to 0.27 meter) per year.

An alternative method of computing the erosion rate can be obtained by making use of the assumption of an exponential profile. The value of B can be determined from equation 3 by finding the value of x when $y - y_o = A$. When $y - y_o = A$, x = B; therefore,

$$A = de^{-\alpha B} \tag{6}$$

or taking logarithms of both sides and rearranging,

$$B = -\frac{1}{\alpha} \ln \frac{A}{d} . \tag{7}$$

Substituting into equation 2,

$$\Delta x = \frac{-A}{\alpha(h + d)} \ln \frac{A}{d} . \tag{8}$$

For the example problem

$$\Delta x = \frac{-0.0054}{0.000564(78.0)} \ln \frac{-0.0054}{55} = 1.13 \text{ feet (0.34 meter) per year} .$$

This estimate is within the bounds computed from equation 2 although it is significantly less than the value computed for B = 32,600 feet. It is based on consistent assumptions regarding the geometry of the profiles.

V. SUMMARY AND CONCLUSIONS

A method for estimating the long-term average retreat rate of a sandy shoreline resulting from a long-term change in mean sea level was developed. The method is approximate and is intended to supplement conventional analyses of historical profile and shoreline changes rather than to supplant such analyses. In cases where little or no data are available, a rough estimate of the shoreline retreat rate can be made from recent profiles and sea level change data available in Hicks (1973).

Offshore profiles can, in many cases, be described by an exponential curve and long-term erosion rates calculated from the equation,

$$\Delta x = \frac{-A}{\alpha(h + d)} \ln \frac{A}{d} ,$$

where $-(1/\alpha) \ln (A/d) = B$ = the distance from shore of the d, depth contour.

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APPENDIX

TRENDS AND VARIABILITY OF YEARLY MEAN SEA LEVEL

Trends and variability of yearly mean sea level through 1971[a]

(1) Location	(2) Date series began	(3) Dates of missing data	(4) Trend[b]	(5) Standard error of trend[c]	(6) Variability[d]	(7) Trend	(8) Standard error of trend	(9) Variability
			ft yr^{-1}	± ft yr^{-1}	± ft	ft yr^{-1}	± ft yr^{-1}	± ft
Atlantic Coast								
1. Eastport, Me.	1930	1957,58,70,71	.0104	.0010	.0711	.0111	.0016	.0771
2. Portland, Me.	1912	1970,71	.0067	.0007	.0905	.0053	.0019	.0892
3. Portsmouth, N. H.	1927	1935-39	.0078	.0009	.0721	.0057	.0013	.0688
4. Boston, Mass.	1922		.0093	.0008	.0833	.0039	.0014	.0731
5. Woods Hole, Mass.	1933	1965,67-69	.0110	.0011	.0696	.0096	.0015	.0679
6. Newport, R. I.	1931		.0096	.0009	.0694	.0074	.0013	.0666
7. New London, Conn.	1939		.0082	.0013	.0700	.0079	.0014	.0708
8. Willets Pt., N. Y.	1932		.0100	.0011	.0839	.0082	.0016	.0847
9. New York, N. Y.	1893		.0093	.0004	.0888	.0096	.0014	.0708
10. Sandy Hook, N. J.	1933		.0155	.0011	.0758	.0155	.0015	.0777
11. Atlantic City, N. J.	1912	1921,22,70,71	.0125	.0007	.0901	.0094	.0017	.0829
12. Baltimore, Md.	1903		.0109	.0005	.0841	.0088	.0015	.0804
13. Annapolis, Md.	1929	1969,70	.0135	.0010	.0798	.0105	.0015	.0747
14. Washington, D. C.	1932		.0096	.0013	.0985	.0089	.0019	.0995
15. Solomons, Md.	1938	1970	.0118	.0014	.0775	.0115	.0016	.0798
16. Hampton Roads, Va.	1928		.0146	.0011	.0950	.0112	.0017	.0880
17. Portsmouth, Va.	1936		.0117	.0013	.0831	.0117	.0017	.0866
18. Charleston, S. C.	1922		.0116	.0011	.1150	.0063	.0022	.1156
19. Fort Pulaski, Ga.	1936		.0079	.0017	.1040	.0067	.0020	.1058
20. Fernandina, Fla.	1939		.0049	.0020	.1078	.0042	.0021	.1071
21. Mayport, Fla.	1929		.0084	.0013	.1069	.0051	.0020	.1058
22. Miami Beach, Fla.	1932		.0080	.0010	.0740	.0061	.0014	.0746
Gulf Coast								
23. Key West, Fla.	1913		.0068	.0006	.0845	.0025	.0016	.0830
24. Cedar Key, Fla.	1915	1926-38	.0066	.0008	.0962	.0024	.0019	.0978
25. Pensacola, Fla.	1924		.0075	.0012	.1184	.0017	.0021	.1076
26. Eugene I., La.	1940	1967,71	.0302	.0024	.1194	.0302	.0024	.1194
27. Galveston, Tex.	1909		.0188	.0011	.1539	.0133	.0027	.1411
West Coast								
28. San Diego, Calif.	1906		.0064	.0005	.0817	.0043	.0017	.0901
29. La Jolla, Calif.	1925	1954,55	.0060	.0009	.0874	.0056	.0018	.0962
30. Los Angeles, Calif.	1924		.0020	.0009	.0883	-.0017	.0016	.0860
31. Alameda, Calif.	1940		.0014	.0023	.1203	.0014	.0023	.1203
32. San Francisco, Calif.	1898		.0064	.0006	.1030	.0054	.0022	.1140
33. Crescent City, Calif.	1933		-.0020	.0014	.1012	-.0052	.0019	.0982
34. Astoria, Oreg.	1925		-.0003	.0014	.1328	-.0025	.0024	.1271
35. Seattle, Wash.	1899		.0062	.0006	.0997	.0081	.0018	.0948

See footnotes at end of table.

(from Hicks, 1973)

Trends and variability of yearly mean sea level through 1971[a] (continued)

(1) Location	(2) Date series began	(3) Dates of missing data	(4) Trend[b]	(5) Standard error of trend[c]	(6) Variability[d]	(7) Trend	(8) Standard error of trend	(9) Variability
			ft yr^{-1}	± ft yr^{-1}	± ft	ft yr^{-1}	± ft yr^{-1}	± ft
36. Neah Bay, Wash.	1935	1959	-.0029	.0016	.1006	-.0047	.0020	.1021
37. Friday Harbor, Wash.	1934	1970	.0034	.0015	.0997	.0020	.0019	.1018
38. Ketchikan, Alaska	1919		.0002	.0011	.1181	-.0000	.0026	.1371
39. Sitka, Alaska	1938		-.0073	.0017	.0970	-.0073	.0019	.1001
40. Juneau, Alaska	1936		-.0440	.0019	.1206	-.0442	.0024	.1271
41. Yakutat, Alaska	1940		-.0171	.0022	.1143	-.0171	.0022	.1143
42. Honolulu, Hawaii	1905		.0053	.0007	.1173	.0004	.0019	.0988
43. Cristobal, C. Z.	1909		.0037	.0005	.0677	.0008	.0010	.0506

[a] Columns 4 - 6: entire series. Columns 7 - 9: 1940-71.

[b] Slope of a least-squares line of regression:

$$b = \frac{\Sigma xy - \frac{(\Sigma x)(\Sigma y)}{n}}{\Sigma x^2 - \frac{(\Sigma x)^2}{n}}$$

Where y = height of yearly mean sea level,
x = date, and
n = number of yearly mean sea-level values.

[c] Standard Error of Slope:

$$s_b = \frac{s_{y.x}}{\sqrt{\Sigma x^2 - \frac{(\Sigma x)^2}{n}}}$$

Where $s_{y.x}$ = Standard Error of Estimate.

[d] Standard Error of Estimate (standard deviation from line of regression):

$$s_{y.x} = \sqrt{\frac{\Sigma y^2 - \frac{(\Sigma y)^2}{n} - b\left(\Sigma xy - \frac{(\Sigma x)(\Sigma y)}{n}\right)}{n - 2}}$$

[e] 1893-1920, Ft. Hamilton; 1921-71, The Battery.

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